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ADAPTATION OF A FREON-12 CHF CORRELATION TO APPLY FOR WATER IN UNIFORMLY HEATED VERTICAL TUBES

PART 2 : BASED ON CHF DATA FOR WATER PRESSURES IN THE RANGE 6-20 MPa

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W.J. GREEN

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ABSTRACT

An examination of more than 5000 sets of experimental data for critical heat flux (CHF) in uniformly heated vertical tubes internally cooled by high pressure water has shown that the CHF correlation proposed in Part 1 of this work is accurate for water at pressures up to approximately 17 MPa, provided that minor modifications are made to the Prandtl number index, and the saturation boiling length function.

For pressures greater than 17 MPa, CHF values calculated from the correlation are increasingly lower than the experimental data, particularly at low saturation boiling length ratios ($L_s/D < 100$). This deficiency results

(Continued)

from the significance of the surface tension number in the correlation and the accuracy to which the values of surface tension and latent heat are known as they approach zero at the critical pressure. As in the previous work, data have been excluded in which either the mass flux is less than 300 kg s^{-1} m^{-2} or thermal equilibrium exit qualities are less than 0.1.

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FREONS; CRITICAL HEAT FLUX; CORRELATIONS; WATER; TUBES; MEDIUM PRESSURE; HIGH PRESSURE; PRANDTL NUMBER; EXPERIMENTAL DATA; COOLANTS; SURFACE TENSION

CONTENTS

(Continued)

1. INTRODUCTION

The development of an accurate critical heat flux (CHF) correlation which represents Freon-12 experimental data over a wide range of coolant conditions has been described in an earlier work [Green 1981a]. Because of the accuracy with which the proposed correlation was able to correlate Freon-12 experimental data, and as an indication that it might be more generally applicable, the correlation was compared with CHF data from other fluids.

Since vast numbers of experimental CHF data have been obtained for uniformly heated vertical tubes cooled by water in a wide range of conditions, it was appropriate that these data should be considered first. In Part 1 of this work [Green 1981b], comparisons were made with water data in the pressure range 3-14 MPa. These showed that for the 2063 data sets examined, there was good agreement between predicted and experimental values over a wide range of coolant conditions.

For coolant pressures greater than 12 MPa, only a limited amount of data was examined and it did not cover a very extensive range of saturation boiling length ratios (L_s/D).

The objective of the present work was to examine in detail experimental CHF data for a wider range of water pressures (up to 20 MPa).

2. CORRELATION RESULTING FROM EXAMINATION OF FREON-12 DATA AND WATER DATA IN THE PRESSURE RANGE 3-12 MPa

Although much experimental CHF data for Freon-12 has been examined by Green [1981a], the range of vapour Prandtl numbers investigated was only 0.9 to 1.02. Hence evaluation of the index of this dimensionless group was difficult and not particularly accurate. Similarly, evaluations of the short tube and low flow modifying components were made for limited ranges of coolant pressures. It was argued by Green [1981b] that if the correlation were truly general, any discrepancies between predicted CHF values and experimental water data should be taken into account by only minor variations in these three parameters.

From the comparisons described in Part 1 of this work [Green 1981b], it was found that minor modifications to the index of the Prandtl number and the short tube modifying factor were indeed necessary. The correlation then became

$$\frac{\phi D}{\mu_v \lambda} = \frac{1}{17000} Re_v^n \left(\frac{\rho_\ell}{\rho_v}\right)^m Pr_v^q \left[\sigma_N\right]^p f\,(L_s/D) \quad (1+\delta)(1-\delta_1)$$

where

$$n = 1-e^{-0.0067\,L_s/D}$$

$$\sigma_N = \frac{\sigma}{\rho_v \lambda D}$$

$$m = 0.1 + e^{-0.007\,L_s/D}$$

$$p = -0.5(0.15 + e^{-0.007\,L_s/D})$$

$$q = -(0.22 + 0.6\,e^{-0.011\,L_s/D})$$

$$f(L_s/D) = e^{4.25\,e^{-0.00366\,L_s/D}}$$

$$\delta = \left(e^{-0.14 \times 10^8\,\sigma_N}\right)\left(e^{-0.02(L/D)Pr_v}\right)$$

$$\delta_1 = 0.75 \exp\{-B(L/D)\,G\sigma/\rho_\ell \mu_\ell \lambda\}$$

$$B = 130.5 \exp\{5.0 \exp(-0.02L/D)\}$$

This correlation adequately describes experimental CHF data for the following coolant conditions:

(i) local pressures in the range 3.4 to 12 MPa;
(ii) mass flux greater than approx. 300 kg s^{-1} m^{-2}; and
(iii) thermal equilibrium value of exit quality greater than 0.1.

For the limited amount of data obtained at pressures greater than 12 MPa, it was observed that agreement between predicted and experimental values was limited.

3. COMPARISON OF CALCULATED AND EXPERIMENTAL CHF VALUES FOR WATER IN THE PRESSURE RANGE 6-20 MPa

Zenkevich et al. [1969] compiled CHF experimental data for water in uniformly heated vertical tubes. In contrast to Thompson and Macbeth [1964], Zenkevich et al. concentrated on data obtained at higher pressures (up to 20 MPa) and much longer heated tubes (aspect ratios up to 1050). Such data are therefore suitable for further testing the generality of the correlation.

When calculated CHF values were compared with the experimental data presented by Zenkevich et al., the following effects of saturation boiling length and higher coolant pressures were found (see Figure 1):

(a) At pressures greater than approx. 10 MPa, it became more obvious that the ratio of the calculated to experimental CHF decreased for saturation boiling length ratios less than approx. 50 and increased for saturation boiling length ratios in the range 50-300, with the maximum increase being at an L_s/D of approx. 120.

(b) At saturation boiling length ratios greater than approx. 500, the ratio of the calculated to experimental CHF increased with increasing L_s/D ratio; this change was apparently independent of pressure.

These two observations were interpreted as indicating two minor deficiencies in the correlation given in Part 1 of this work. First, the correlation overpredicted experimental data by increasing amounts at L_s/D ratios greater than approx. 500; this indicated that the $f(L_s/D)$ term in the correlation needed reconsideration since the observed effect was independent of coolant conditions. Previously, only experimental data involving saturation boiling length ratios less than 600 were examined [Green 1981a,b]. Second, the effect of coolant pressure at L_s/D ratios below approx. 300 could be attributed to the need to define more precisely the index of the Prandtl number. As argued in Part 1 [Green 1981b], if the correlation is general, any discrepancy between experimental and calculated CHF values can only be ascribed to vapour Prandtl number. The index of the vapour Prandtl number was determined in Part 1 by using experimental water data at approx. 7.0 MPa. At this pressure, the vapour Prandtl number is approx. 1.5. With increasing pressure, the vapour Prandtl number increases such that for a coolant pressure of 15.7 MPa it is 3.02, and for a coolant pressure of 17.7 MPa it is 4.02.

Obviously minor discrepancies in the vapour Prandtl number index would be more apparent at higher pressures.

4. RE-EVALUATION OF THE VAPOUR PRANDTL NUMBER INDEX

Simply by inspection it would appear that the value of the Prandtl number index is marginally too high at $L_s/D = 0$ and too low at L_s/D approx. 100. The index q was adjusted by a trial and error procedure. This led to q being changed from $-(0.22 + 0.6 \exp(-0.011\, L_s/D))$ to $-(0.21 + 0.55 \exp\{-0.007\, L_s/D\})$.

5. RE-EVALUATION OF THE SATURATION BOILING LENGTH FUNCTION

The saturation boiling length function was originally determined as

$$e^{4.25\, e^{-0.00366\, L_s D}}$$

and found to be valid for L_s/D ratios up to approx. 500. Variation in this function to account for observed deficiencies at L_s/D ratios > 500 needs to take account of the fact that it should not significantly affect values of the function for L_s/D ratios < 500.

Once again by trial and error, a new saturation boiling length function was developed which represents the required relationship. The revised function, together with a revised value for the constant (1/7000) in the correlation, is

$$0.00009 \exp\{-\ 0.00055\, L_s/D + 3.83 \exp(-0.00396\, L_s/D)\} \quad .$$

Comparison of the original and revised saturation boiling length function, including the relevant constants, is shown in Figure 2.

6. COMPARISON OF REVISED CORRELATION WITH EXPERIMENTAL DATA

After including the revised equations for the Prandtl number index and the saturation boiling length function, calculated values of CHF were compared with 4253 experimental data sets, as compiled by Zenkevich et al. (see Figures

3 to 12). Data were omitted in which the dryout thermal equilibrium qualities were less than 0.1.

From Figures 3 to 10 it can be seen that for coolant pressures ranging from 5.9 to 15.7 MPa, the calculated and experimental CHF values agree well. For pressures greater than approx. 16 MPa, a discrepancy between calculated and experimental CHF values appears and worsens as the pressure increases; this indicates that the correlation underpredicts experimental data. At pressures in the range 16 to 18 MPa (see Figures 10 and 11), this discrepancy occurs at L_s/D ratios less than 200 and at mass fluxes which are greater than 1500 kg s^{-1} m^{-2}. For coolant pressures greater than approx. 18 MPa, the error between the calculated and experimental values becomes significantly worse, particularly at saturation boiling length ratios less than 100, and is present at all the mass fluxes investigated. No complete explanation of the failure of the correlation at these coolant conditions has been found, but on close scrutiny the following comments can be made:

(i) Thermal disequilibrium effects are unable to account for the failure.

(ii) A small variation in the surface tension has a significant effect on the calculated surface tension number at high pressures, particularly at low L_s/D ratios. This arises since at the critical point the surface tension becomes zero and is only 2.5 x 10^{-3} N m^{-1} at a coolant pressure of 18 MPa (in contrast to values of 12.0 x 10^{-3} N m^{-1} at a pressure of 10 MPa and 22.7 x 10^{-3} N m^{-1} at 5 MPa).

(iii) The calculation of both the surface tension number and the critical heat flux number are more sensitive to variations or inaccuracies in the value of the latent heat of vaporisation as the critical pressure is approached since, at the critical point, this physical property also becomes zero.

With regard to observations (ii) and (iii), the surface tension has been determined from a relationship between surface tension and saturation temperature recommended by Grigull and Bach [1966]. This recommended relationship was theoretically derived but is considered to be capable of describing experimental data to within ± 1 per cent. Similarly, values of the latent heat of vaporisation have been obtained from internationally accepted steam tables. For both of these properties it would seem, therefore, that although small inaccuracies might explain the discrepancy between calculated CHF values and experimental data, such inaccuracies cannot be attributed to physical property sources. It is only possible to note that discrepancies are present at pressures approaching the critical pressure and that they are most likely related to the calculation of the surface tension number.

Experimental CHF data for water in uniformly heated vertical tubes at pressures between 13.8 and 21.5 MPa have been compiled by Robertson [1971]. Over 700 of these data sets have been examined and the conclusions reached are almost identical to those already described, i.e. the correlation is consistent with experimental data up to pressures of approx. 17 MPa but then becomes increasingly inaccurate.

Table 1 illustrates that the changes made to the correlation have no significant effect on comparisons reported in Part 1.

7. CONCLUSIONS

As a result of further extensive comparisons between a CHF correlation and experimental data for uniformly heated tubes cooled by high pressure water, the equations defining (a) the index of Prandtl number, and (b) the saturation boiling length function, have been slightly modified. These modifications enable the use of the correlation to be extended to cover water pressures up to approx. 17 MPa. Above this pressure there is increasing discrepancy between calculated and experimental CHF values. This may be attributable to inaccuracies in the surface tension number as the surface tension approaches zero.

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9. NOTATION

B	variable, defined in text
C_p	specific heat
CHF	critical heat flux
D	tube bore
G	mass flux
k	thermal conductivity
L	total heated length
L_s	saturation boiling length
m n p q	indices defined in text
Pr	Prandtl number = $C_p\ \mu/k$
Re_v	vapour Reynolds number = $GD/\mu_v\{x + (1-x)\ \rho_v/\rho_\ell\}$
V	velocity
x	mass fraction (quality)
δ	short tube modifying factor
δ_1	low mass flux modifying factor
ρ	density

μ	viscosity
σ	surface tension
σ_N	surface tension number $= \sigma/(\rho_v \lambda D)$
λ	latent heat of vaporisation
ϕ	critical heat flux
ϕ_N	critical heat flux number $= \phi D/(\mu_v \lambda)$

Subscripts

v	vapour
ℓ	liquid

TABLE 1

COMPARISON OF THE ORIGINAL AND REVISED CRITICAL HEAT FLUX CORRELATIONS FOR VERTICAL UPFLOW OF WATER AT PRESSURES OF 3-14 MPa

Source of Data	Pressure (MPa)	No. of Data Examined	Mean Ratio of Calculated to Experimental CHF		r.m.s. Error (%)	
			Using Correlation in Part 1	Using Correlation presented Here	Using Correlation in Part 1	Using Correlation presented Here
Cumo et al. [1979]	7.0	190	1.003	0.986	1.5	2.0
Dell et al. [1969]	6.9	82	0.970	0.951	4.6	5.4
Bennett et al. [1965]	6.6-7.1	161	1.008	0.993	3.7	3.7
Lee [1965]	6.4-7.2	132	1.005	0.988	3.1	3.5
Lee and Obertelli [1963]	3.7-11.1	493	0.973	0.958	5.8	6.6
Lee [1966]	8.2-12.6	262	0.970	0.955	9.6	9.2
Thompson and Macbeth [1964] Table 4	3.4-4.4	163	0.980	0.974	5.7	5.8
Thompson and Macbeth [1964] Table 5	4.9-5.2	31	0.960	0.953	4.5	5.5
Thompson and Macbeth [1964] Table 6	6.6-7.3	451	0.930	0.966	4.7	5.6
Thompson and Macbeth [1964] Table 7	8.8-9.1	15	0.939	0.958	8.4	9.0
Thompson and Macbeth [1964] Table 8	10.4-11.2	83	0.972	0.957	8.0	8.6
Thompson and Macbeth [1964] Table 9	12.1-12.6	33	0.957	0.969	8.5	8.2
Thompson and Macbeth [1964] Table 10	13.8	152	1.029	1.006	12.0	10.9

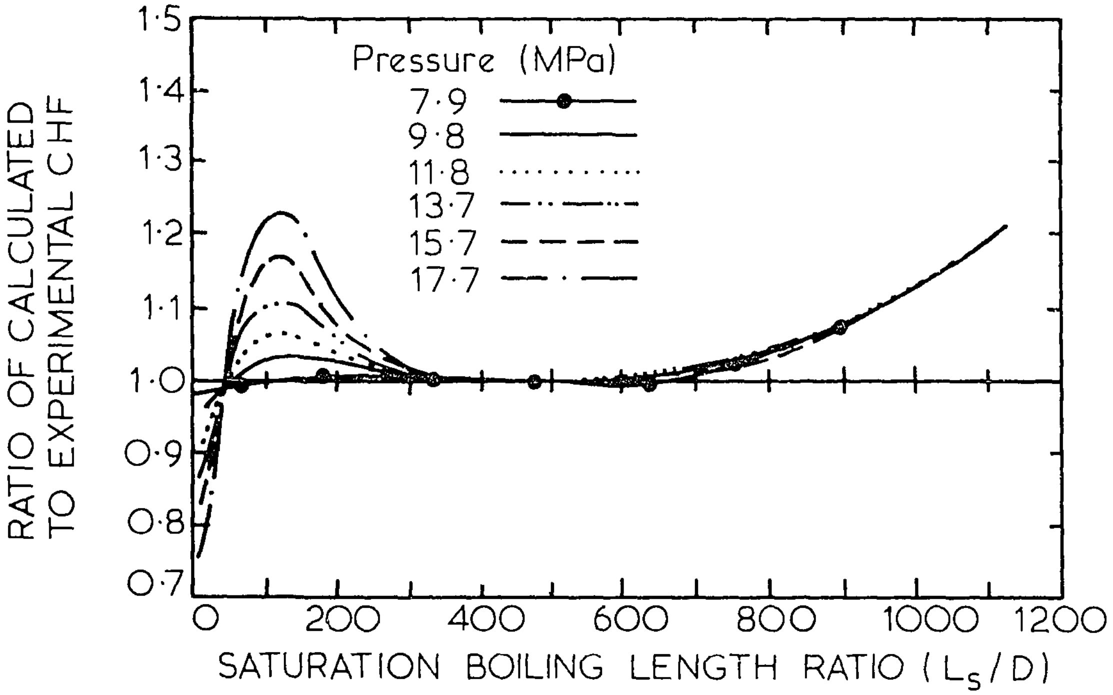

FIGURE 1. EFFECTS OF L_S/D RATIO AND PRESSURE ON RATIO OF CALCULATED TO EXPERIMENTAL CHF FOR WATER, USING EARLIER CORRELATION (GREEN 1981b)

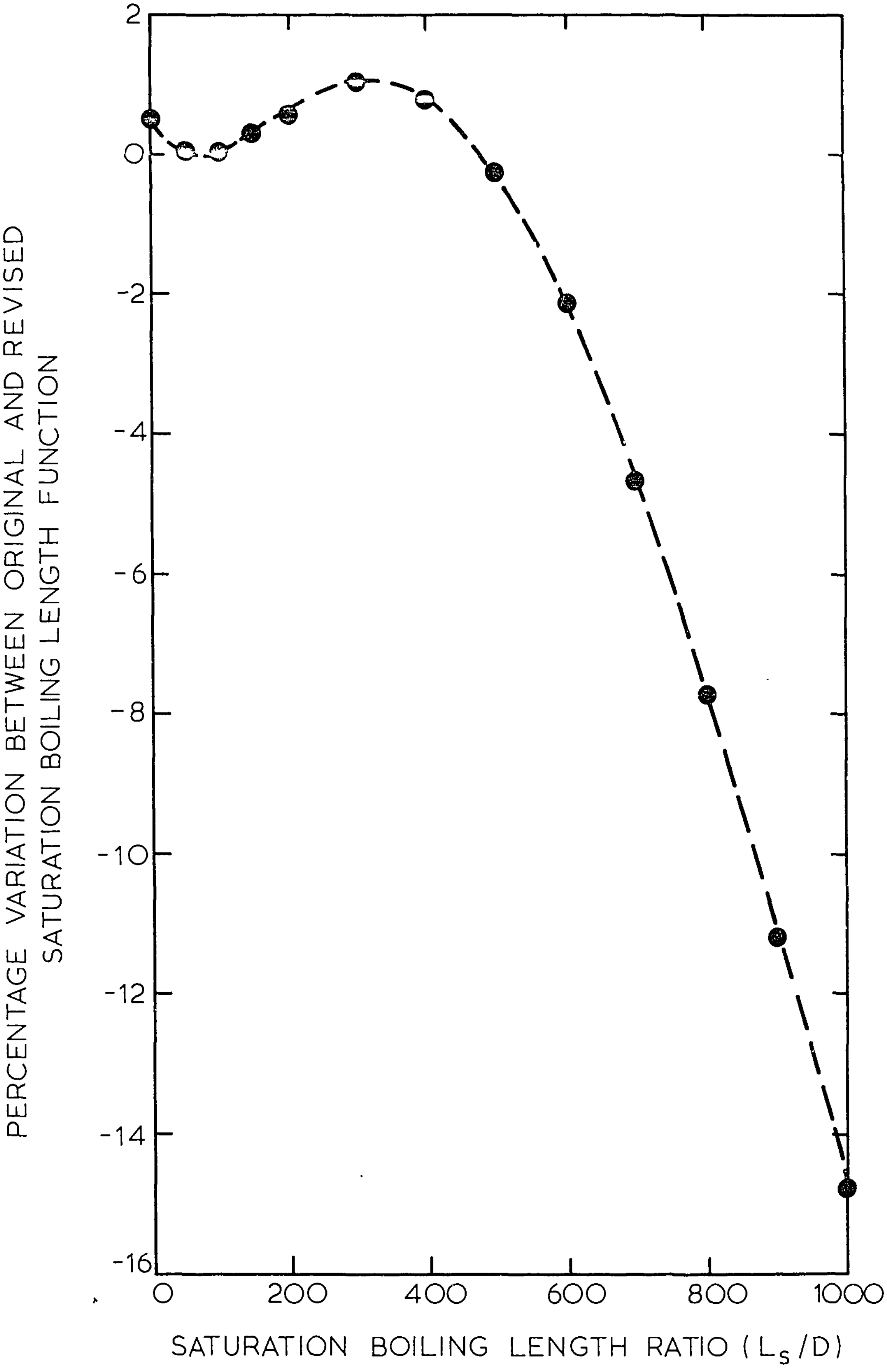

FIGURE 2. COMPARISON OF ORIGINAL AND REVISED SATURATION BOILING LENGTH FUNCTIONS

Note: Experimental CHF values for Figures 3 to 12 are from Zenkevich et al. [1969]

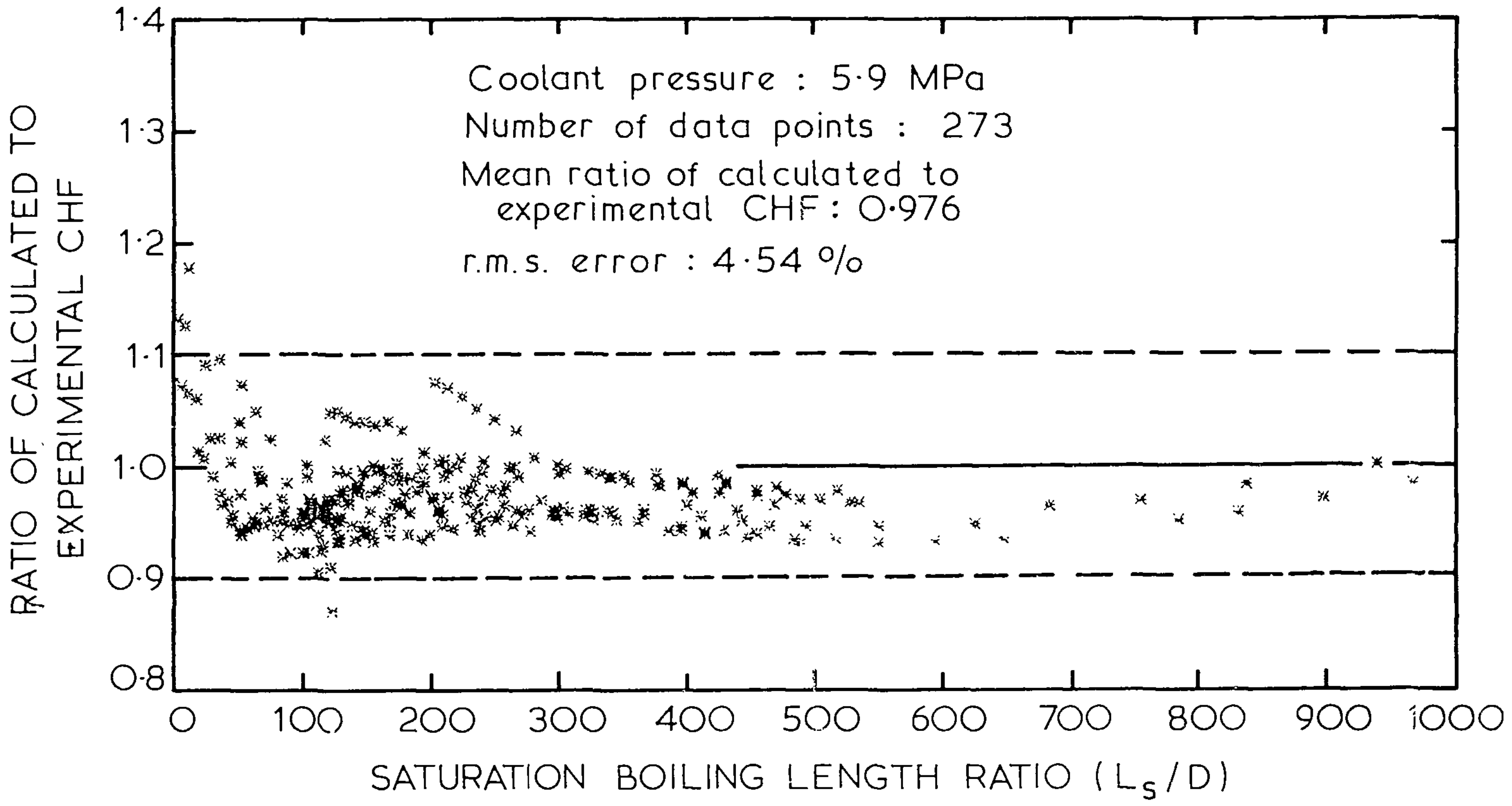

FIGURE 3. COMPARISON OF CALCULATED AND EXPERIMENTAL CHF VALUES (ZENKEVICH : TABLE 16)

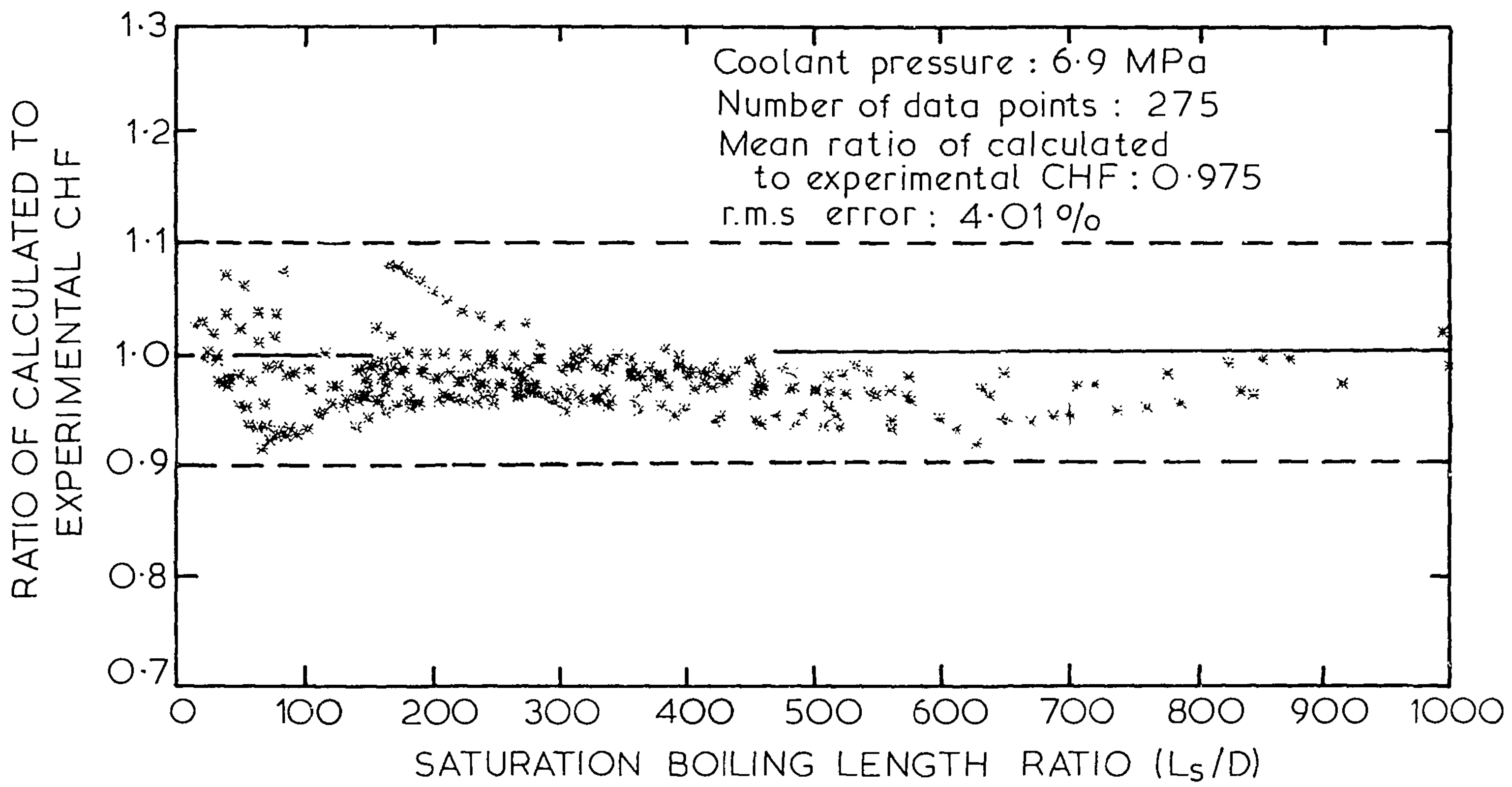

FIGURE 4. COMPARISON OF CALCULATED AND EXPERIMENTAL CHF VALUES (ZENKEVICH : TABLE 18)

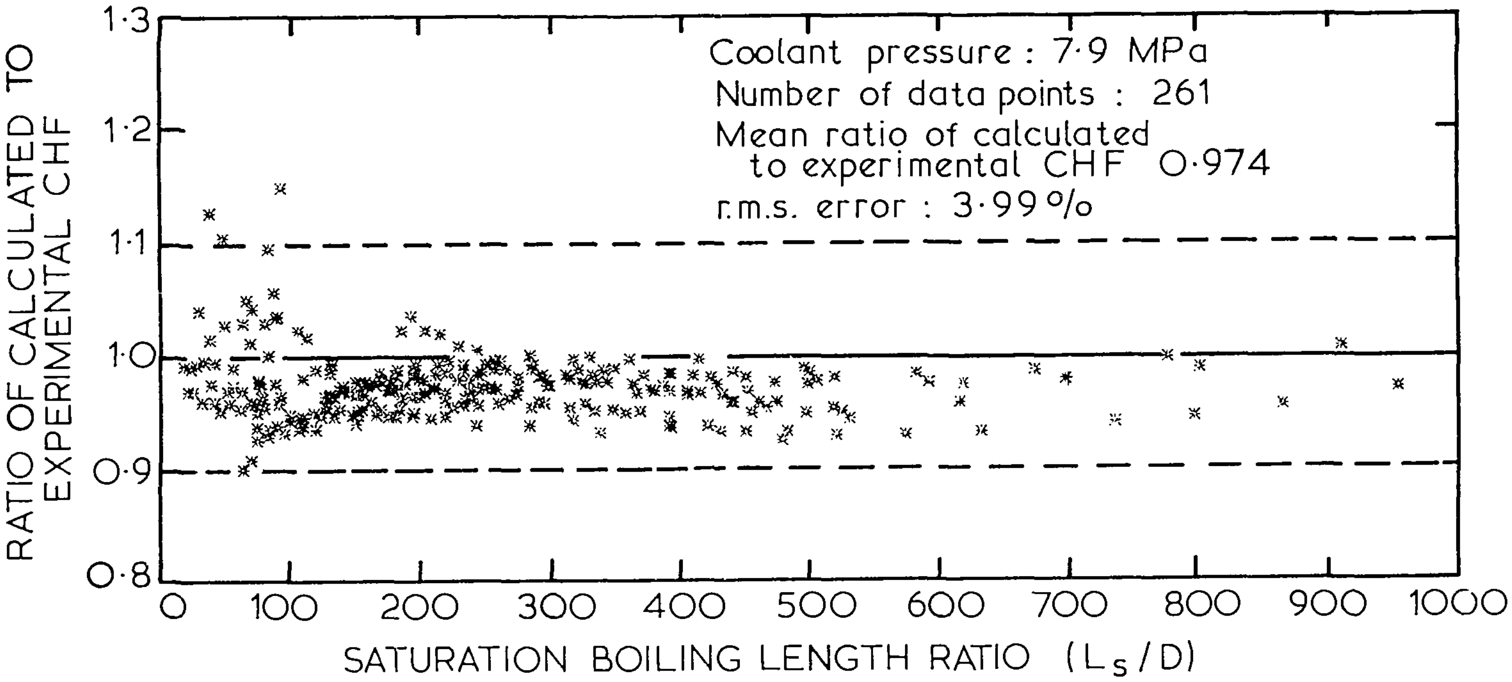

FIGURE 5. COMPARISON OF CALCULATED AND EXPERIMENTAL CHF VALUES (ZENKEVICH : TABLE 20)

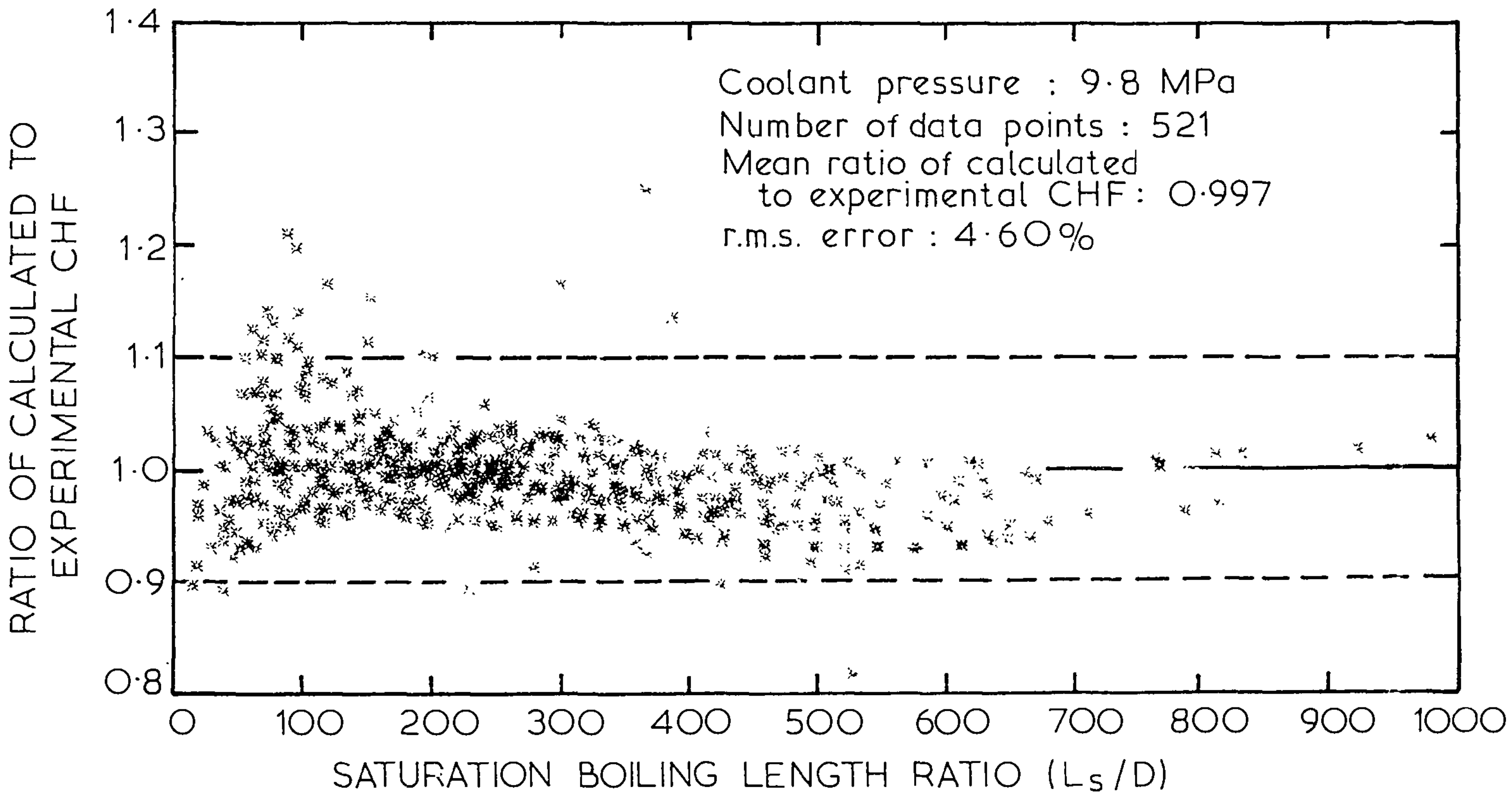

FIGURE 6. COMPARISON OF CALCULATED AND EXPERIMENTAL CHF VALUES (ZENKEVICH : TABLE 22)

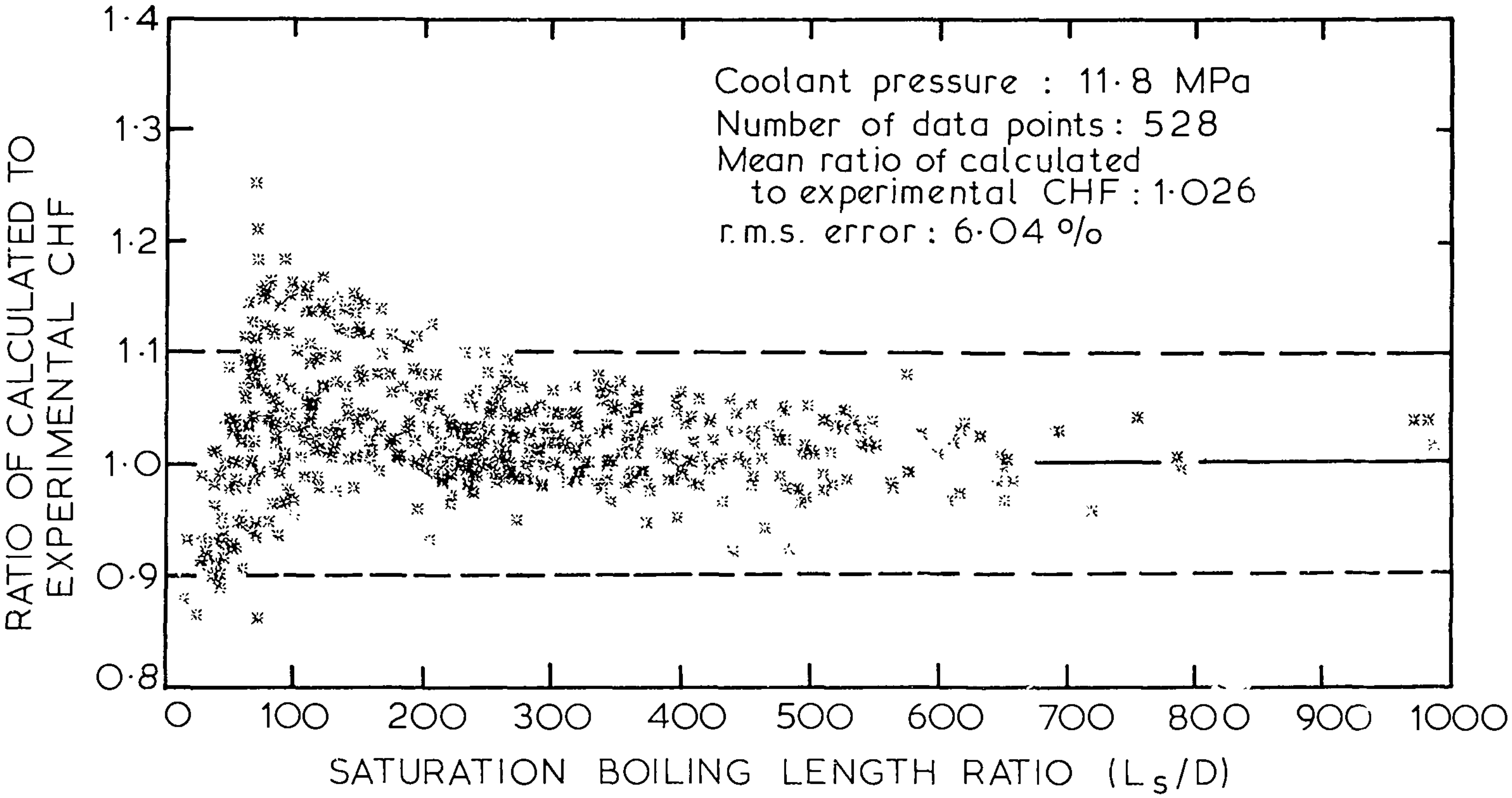

FIGURE 7. COMPARISON OF CALCULATED AND EXPERIMENTAL CHF VALUES (ZENKEVICH : TABLE 24)

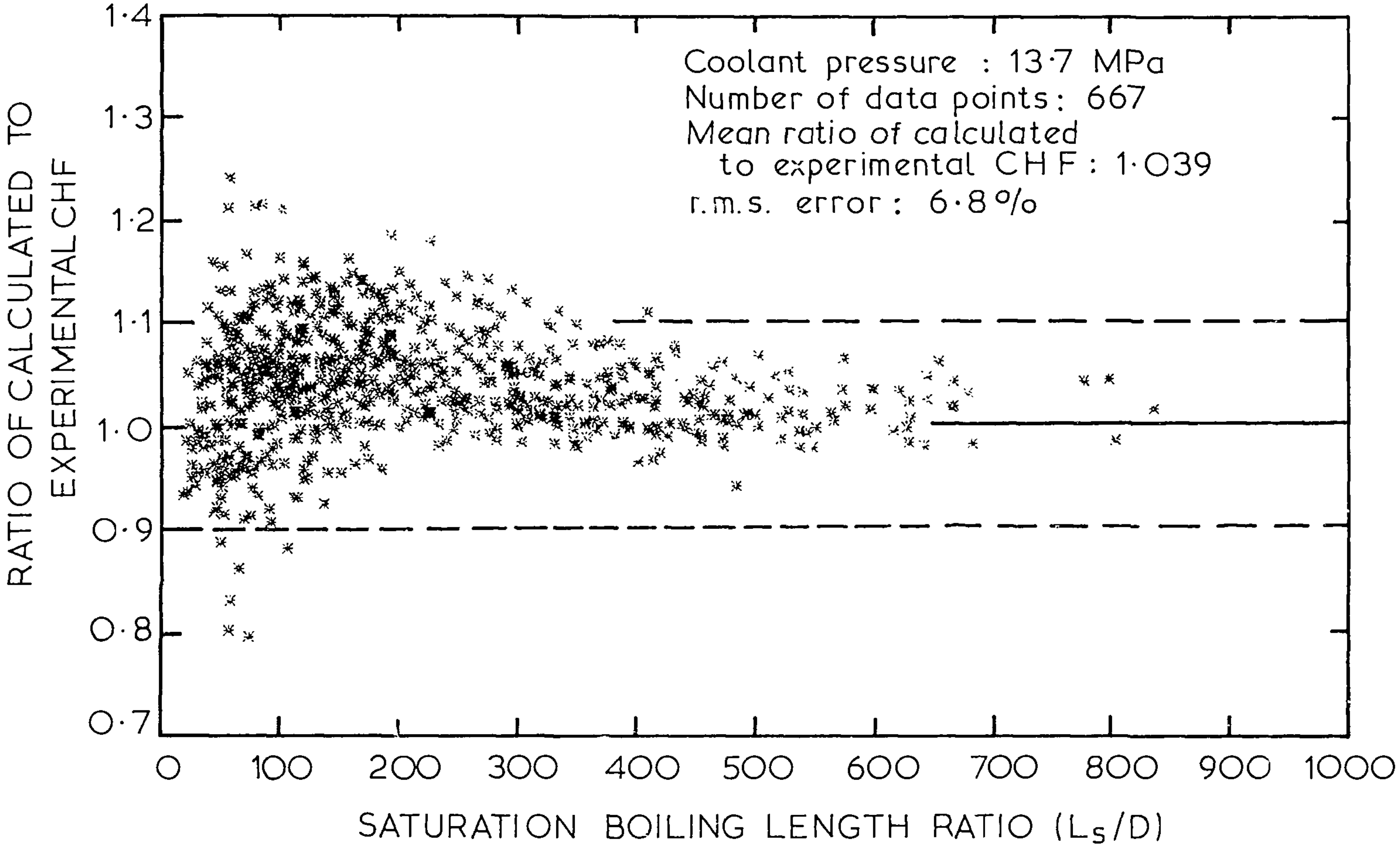

FIGURE 8. COMPARISON OF CALCULATED AND EXPERIMENTAL CHF VALUES (ZENKEVICH : TABLE 26)

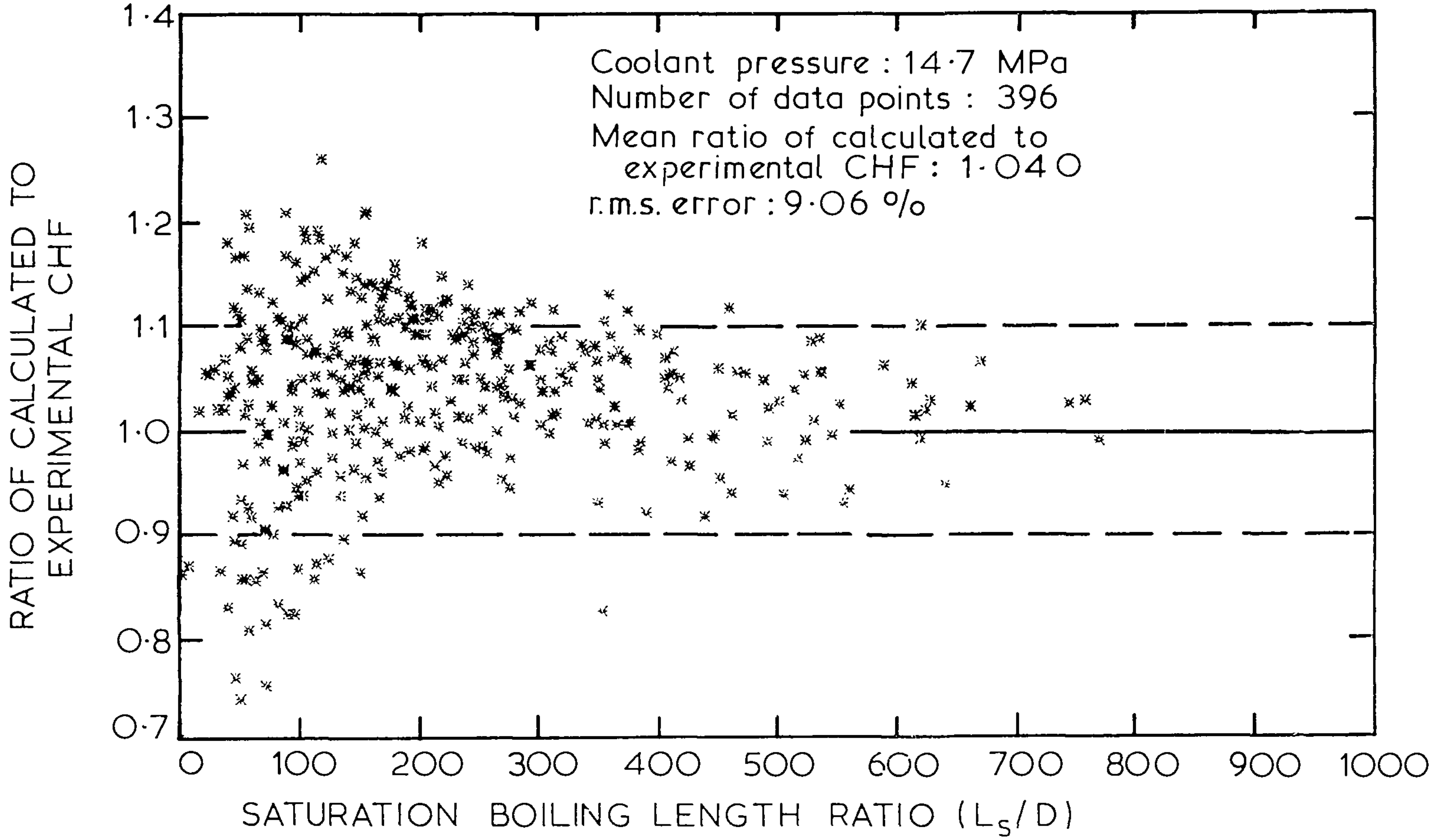

FIGURE 9. COMPARISON OF CALCULATED AND EXPERIMENTAL CHF VALUES (ZENKEVICH : TABLE 28)

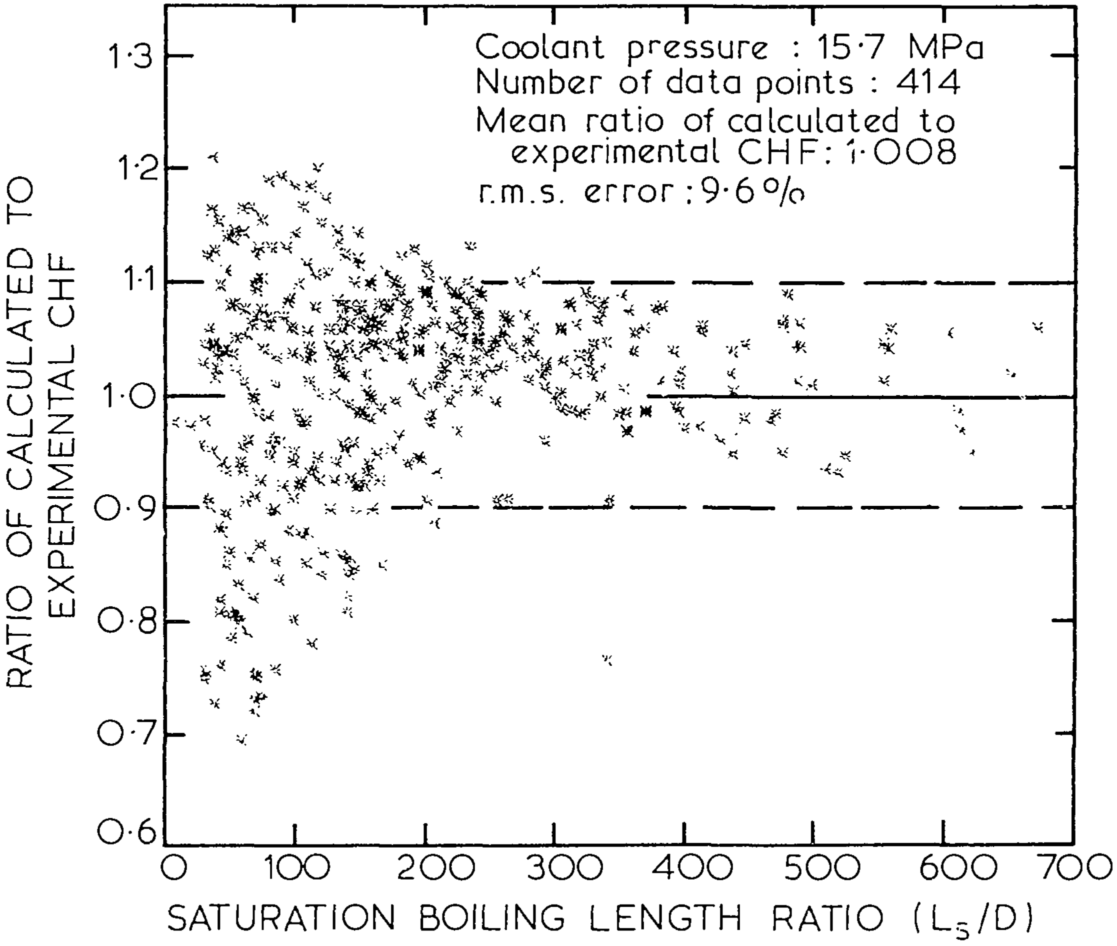

FIGURE 10. COMPARISON OF CALCULATED AND EXPERIMENTAL CHF VALUES (ZENKEVICH : TABLE 30)

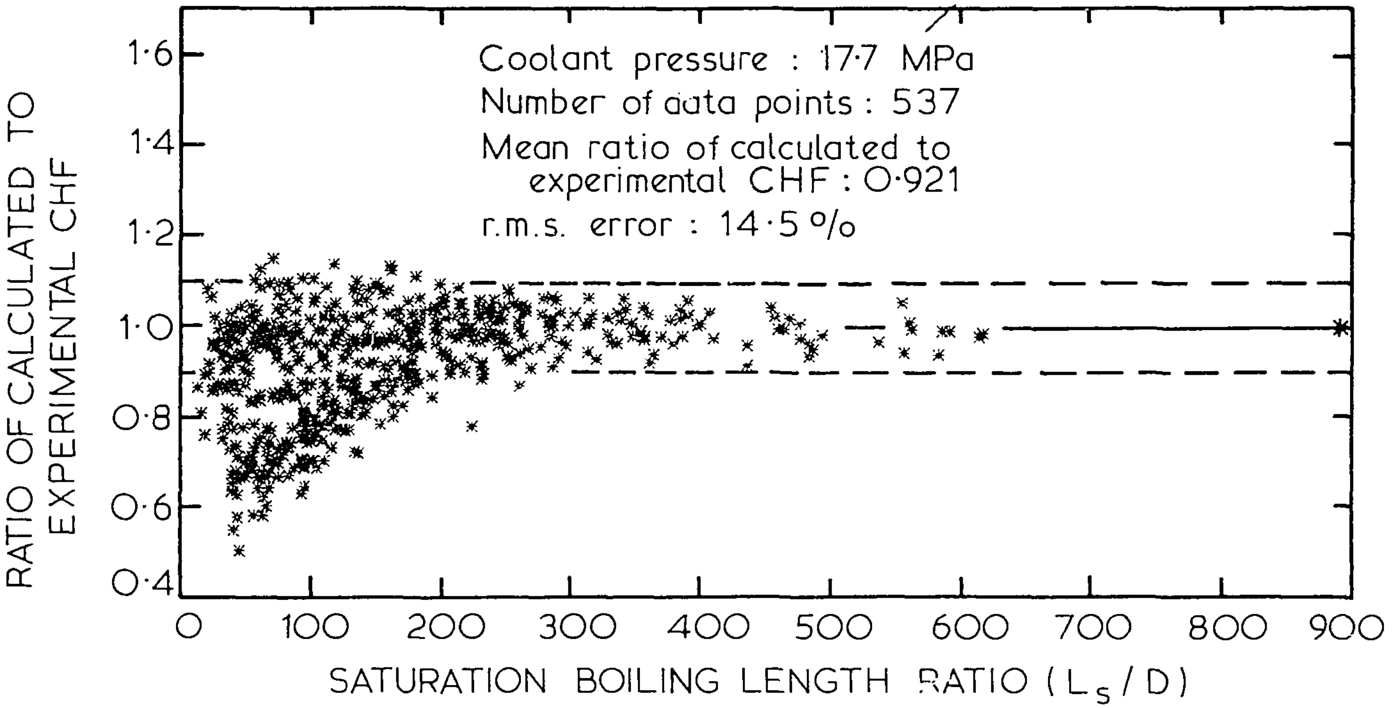

FIGURE 11. COMPARISON OF CALCULATED AND EXPERIMENTAL CHF VALUES (ZENKEVICH : TABLE 32)

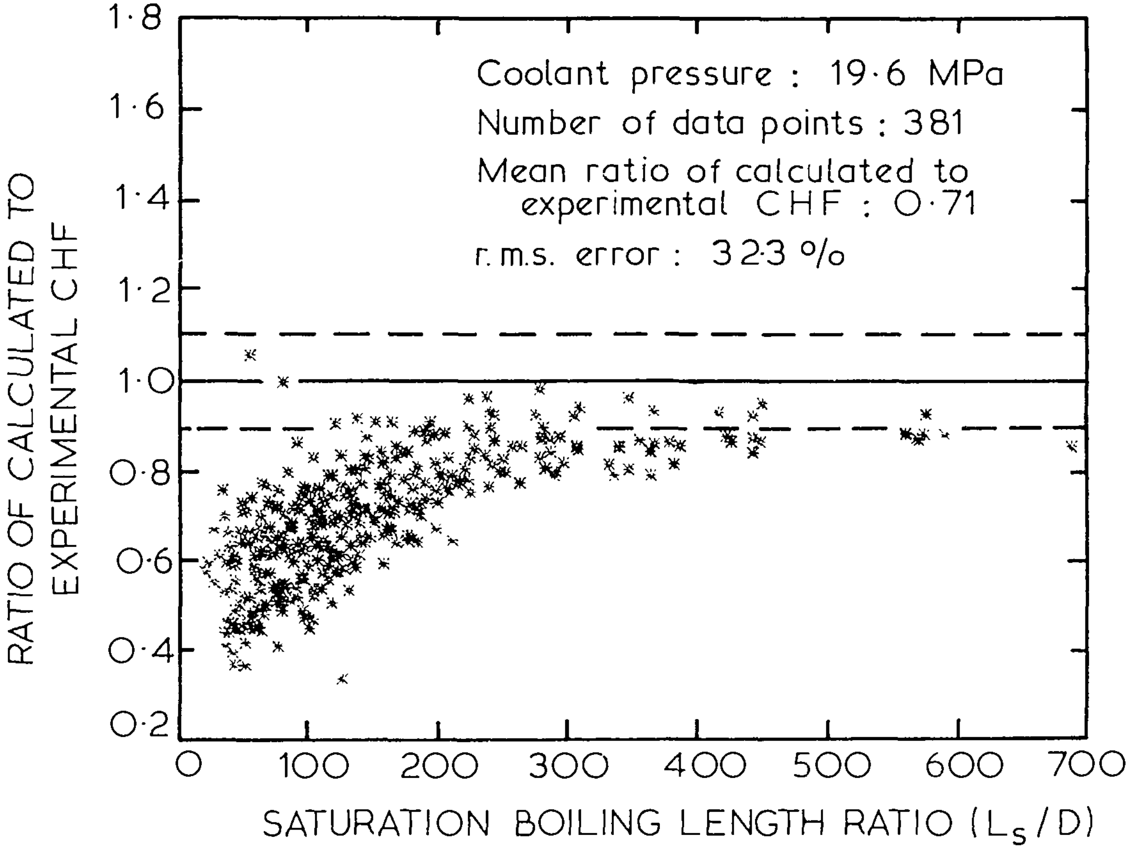

FIGURE 12. COMPARISON OF CALCULATED AND EXPERIMENTAL CHF VALUES (ZENKEVICH : TABLE 34)